

Progress Report on F_L and Diffractive Physics Program to Measure Gluon Distributions in Nuclei

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The Big Questions

NSAC Long Range Plan '07- Overarching Questions:

What is the role of gluons and gluon self-interactions in nucleons and nuclei?

Studying gluons implies measurements of:

1. gluon momentum distributions $G(x, Q^2)$
2. gluon space time distribution

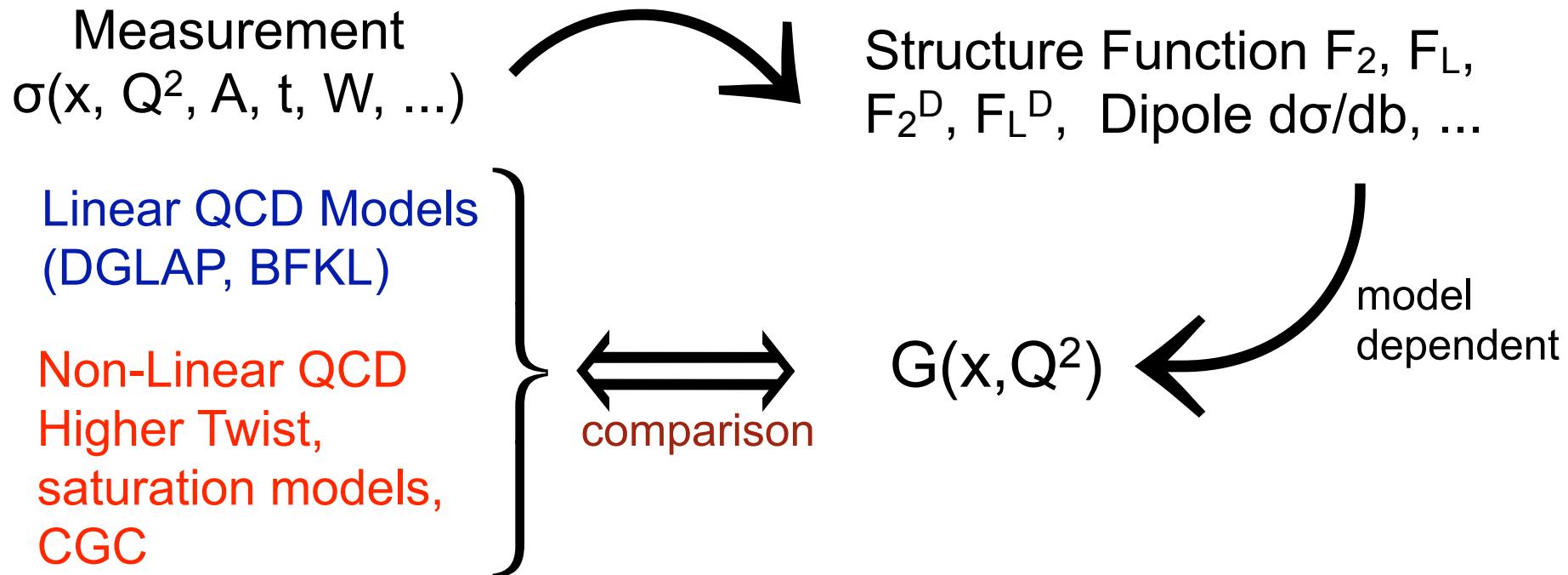
Incremental in ep, transformational in eA

Main Focus (Discovery Potential)

Establishment/Clarification of saturation and validity of CGC approach \Rightarrow one of the fundamental outstanding problems in QCD

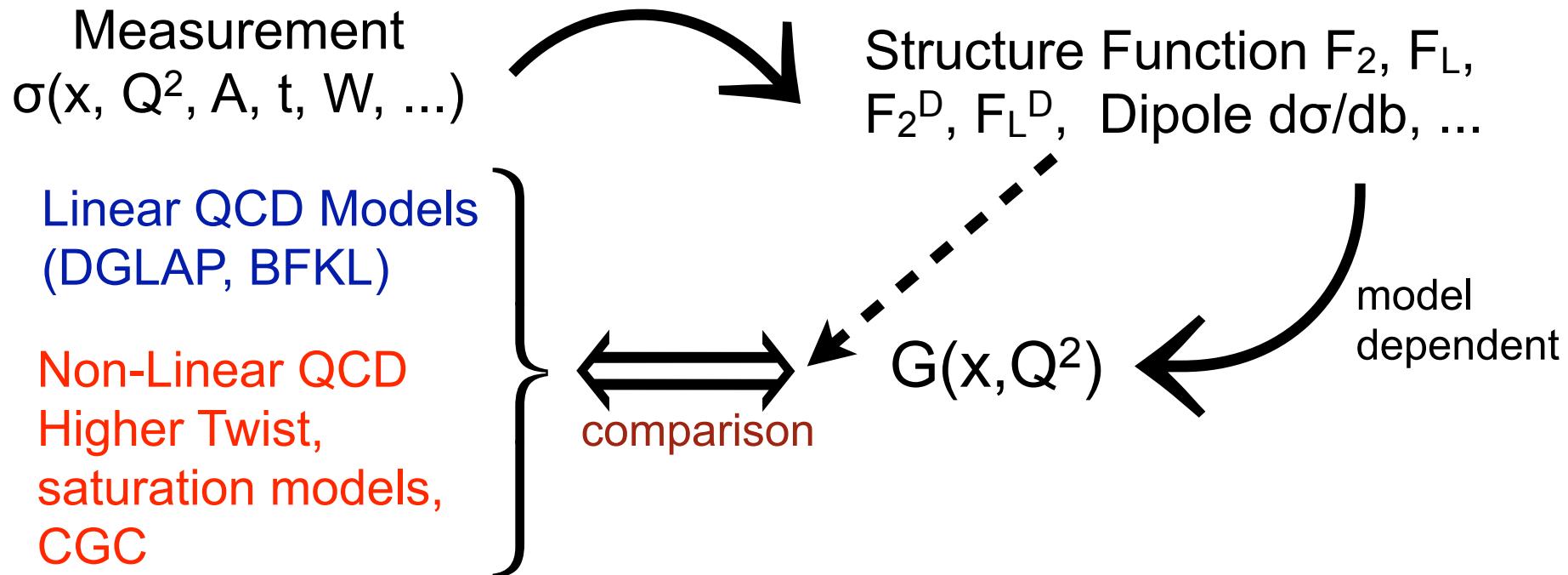
Gluon Distributions and Saturation

How to probe saturation? $G(x, Q^2)$ is not an observable!



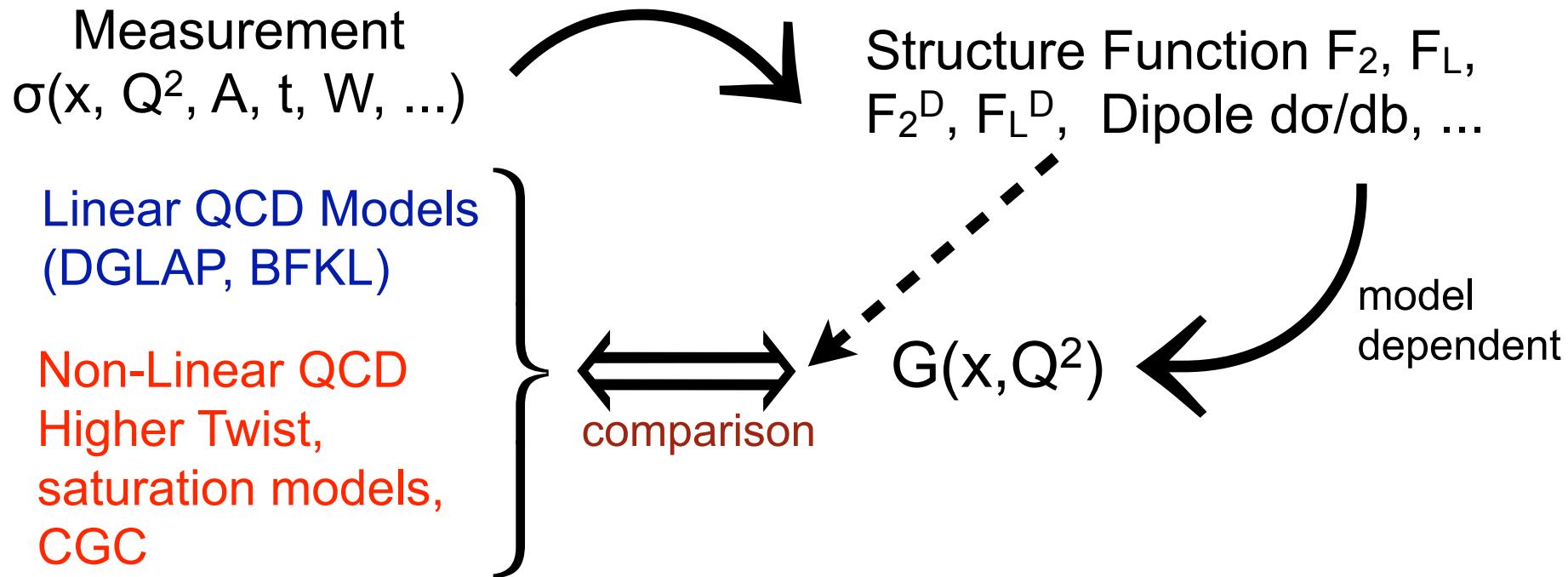
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Gluon Distributions and Saturation

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Comparison (to constrain/reject models) requires

- ▶ “lever arm” in x, Q^2, A, \dots
- ▶ complementary measurements (incl., semi-incl., excl., DIS & diffractive, varying probes, ...)

Measurements & Techniques

- Gluon Distribution $G(x, Q^2)$
 - ▶ Scaling violation in F_2 : $\delta F_2 / \delta \ln Q^2$
 - ▶ $F_L \sim xG(x, Q^2)$
 - ▶ 2+1 jet rates
 - ▶ Diffractive vector meson production ($[xG(x, Q^2)]^2$)
- Space-Time Distribution
 - ▶ Exclusive diffractive VM production ($J/\psi, \phi, \rho$)
 - ▶ Deep Virtual Compton Scattering (nGPDs)
 - ▶ Structure functions for various mass numbers A and its impact parameter dependence

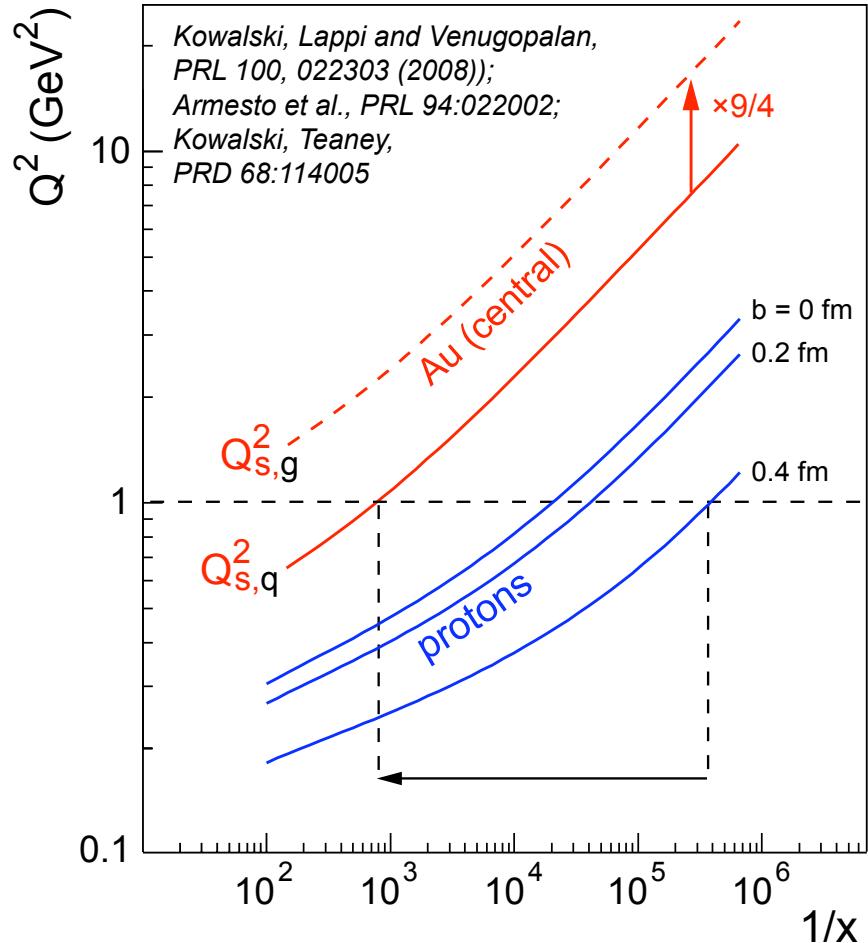


Ongoing studies



On To-Do List

Saturation & Kinematic Range



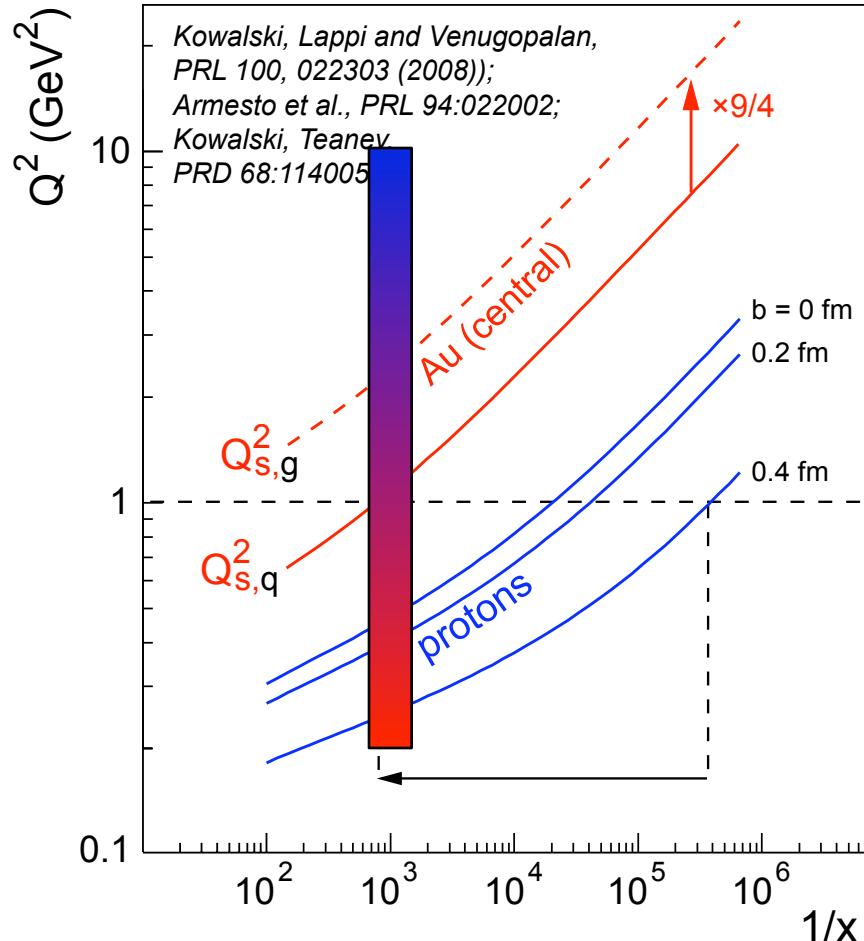
Nuclear Enhancement of Q_s

$$(Q_s^A)^2 \approx c Q_0^2 \left(\frac{A}{x} \right)^{1/3}$$

~6 for Au/U \Rightarrow at fix Q^2 translates into huge increase in x (~500)

pp, pA, AA: $Q_{s,g}$
DIS (ep, eA): $Q_{s,q}$

Saturation & Kinematic Range



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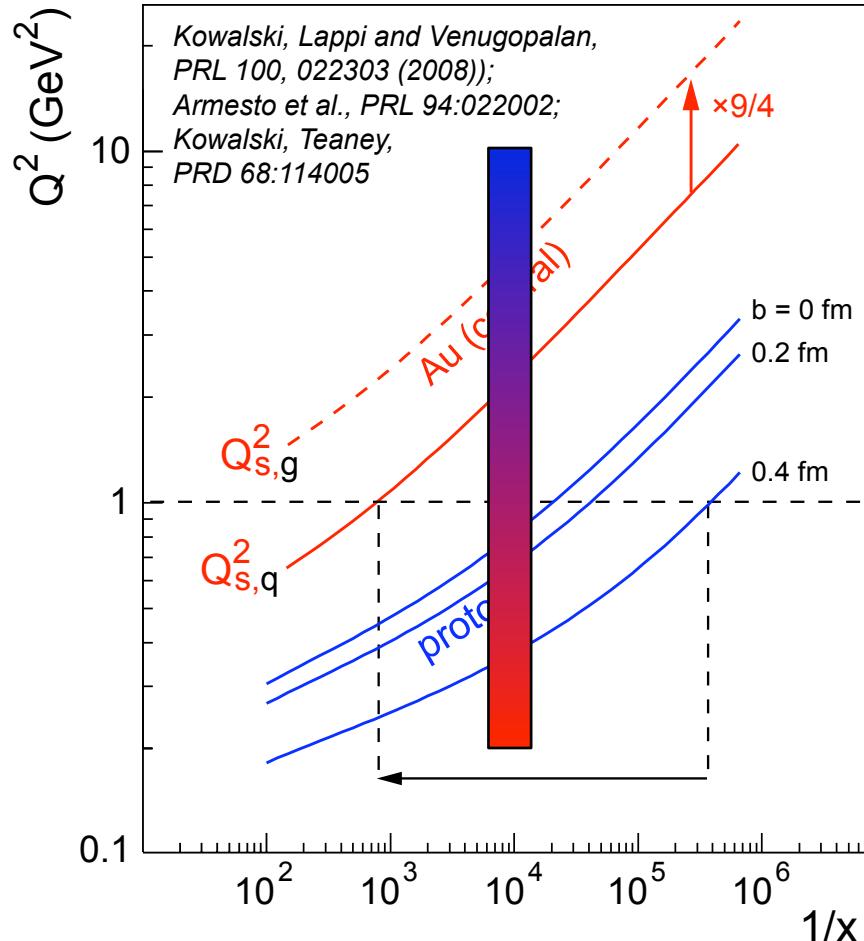
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x, Q^2 kinematics:

$x = 10^{-3}$: $Q^2 = 0.2 \dots 10$ GeV 2
 $\sqrt{s} = 14 \dots 100$ GeV

Saturation & Kinematic Range



$E_e + E_A$ (GeV)	\sqrt{s} (GeV)
4+100	40
10+100	63
20+100	89
30+100	110

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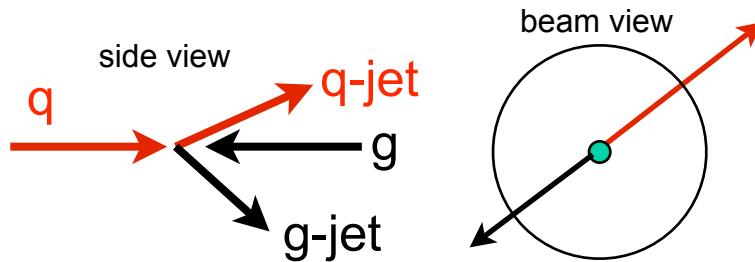
$x = 10^{-3}$: $Q^2 = 0.2 \dots 10 \text{ GeV}^2$
 $\sqrt{s} = 14 \dots 100 \text{ GeV}$

$x = 10^{-4}$: $Q^2 = 0.2 \dots 10 \text{ GeV}^2$
 $\sqrt{s} = 45 \dots 316 \text{ GeV}$

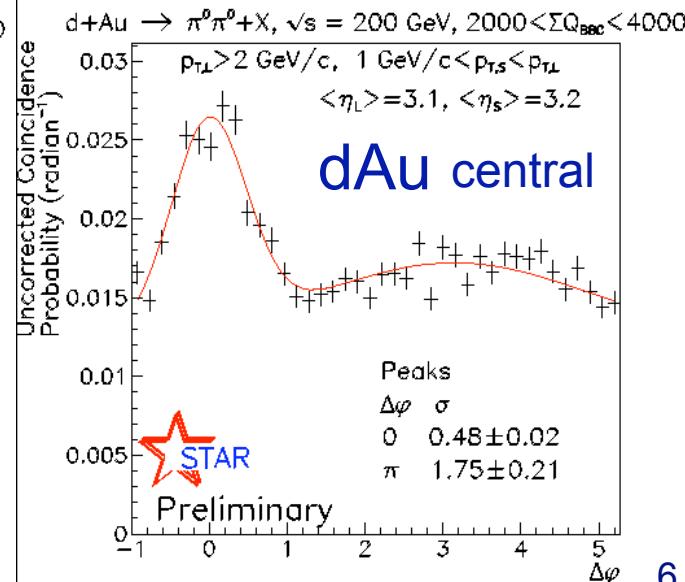
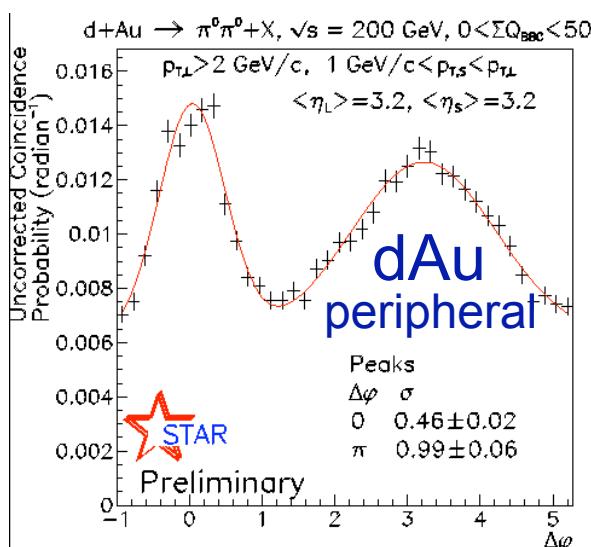
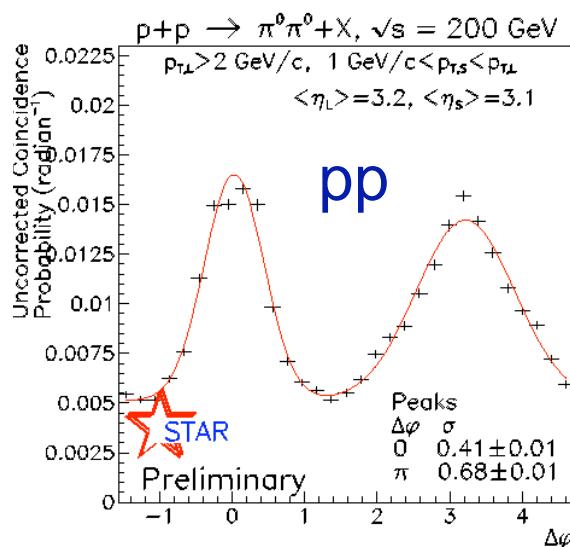
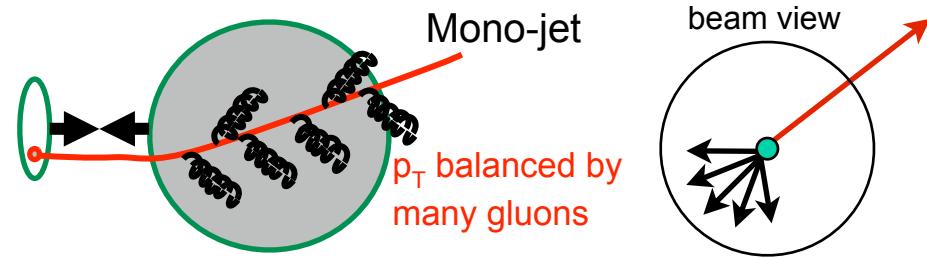
New Hints from RHIC: Saturation at $x=10^{-3}$?

Disappearance of angular correlations in Run 8 dAu data at forward rapidities ($\log x \sim 2.5 - 3$)

Low gluon density (pp):
pQCD predicts $2 \rightarrow 2$ process
 \Rightarrow back-to-back di-jet



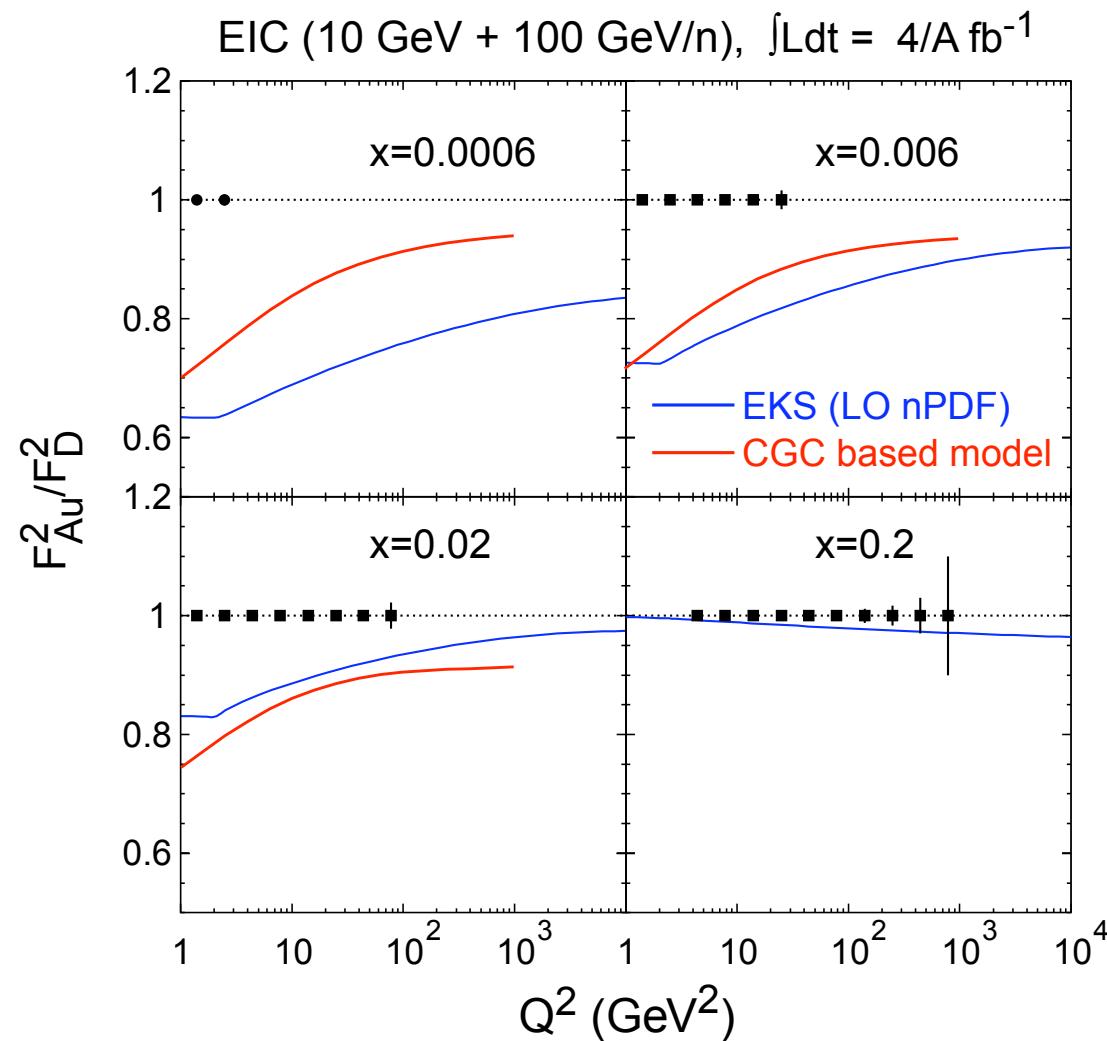
High gluon density (pA):
 $2 \rightarrow 1$ ($2 \rightarrow \text{many}$) process \Rightarrow mono-jet



Measuring F_2 with the EIC

$$\frac{d^2\sigma^{ep \rightarrow eX}}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4} \left[\left(1 - y + \frac{y^2}{2}\right) F_2(x, Q^2) - \frac{y^2}{2} F_L(x, Q^2) \right]$$

Inclusive DIS:
 F_2 is day 1 measurement



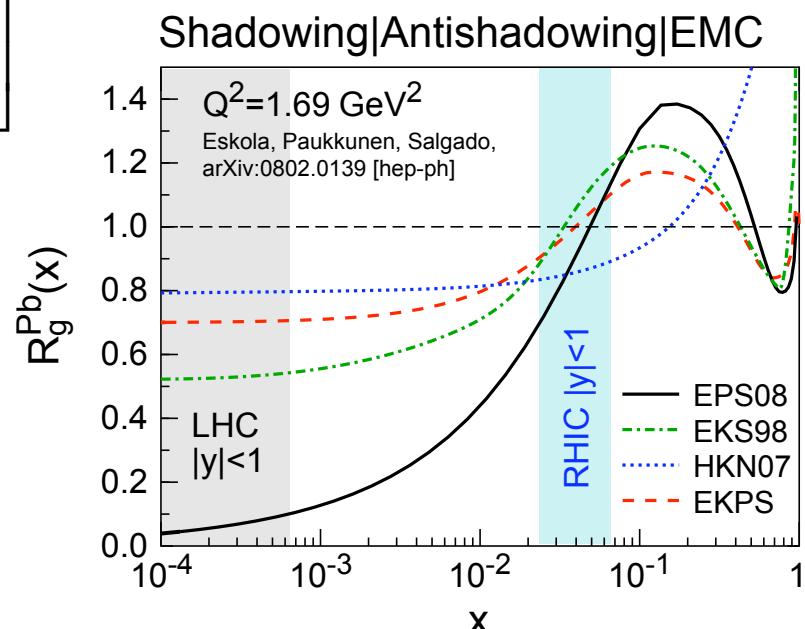
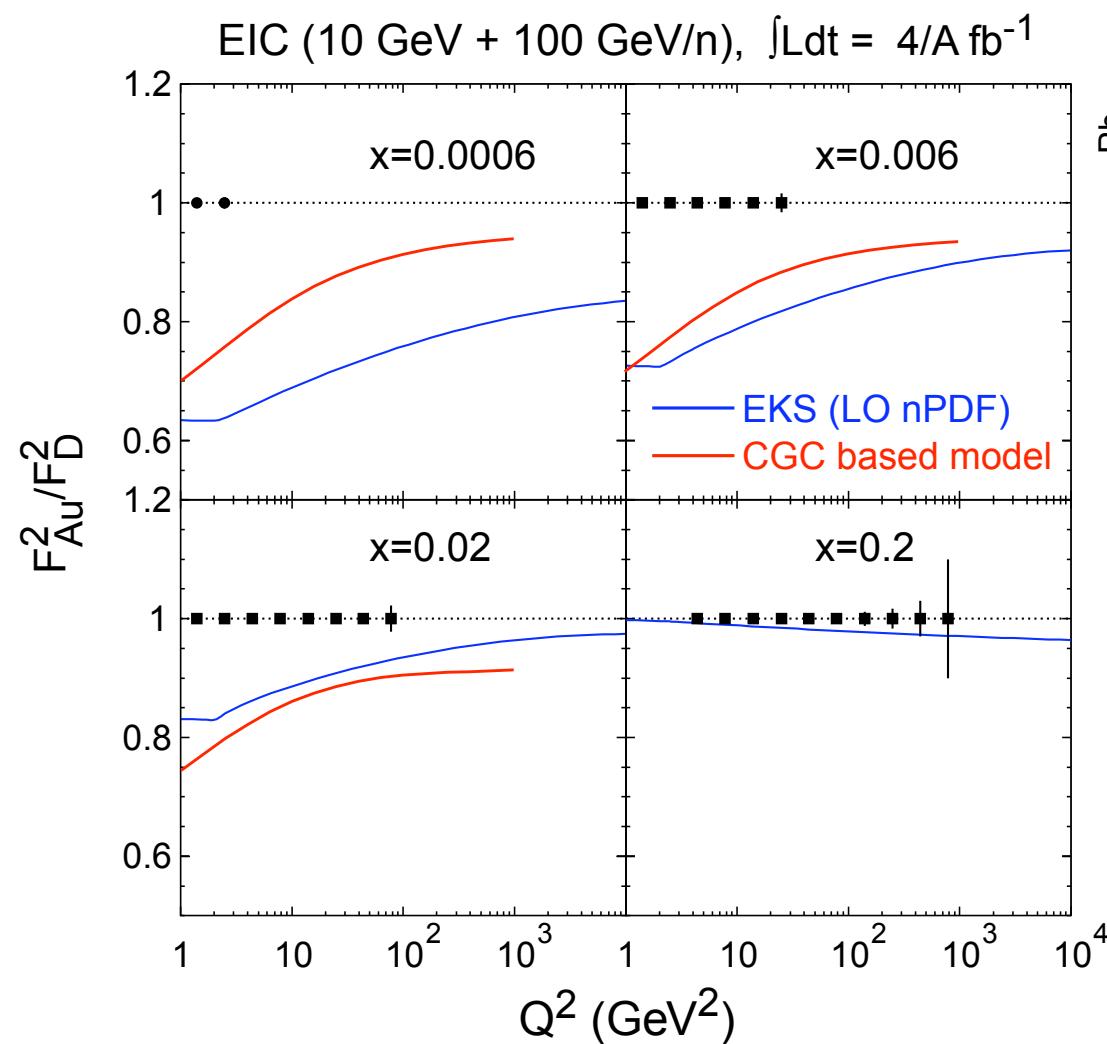
Assumptions:

- 10 GeV + 100 GeV/n
 - ▶ $\sqrt{s} = 63 \text{ GeV}$
- $Ldt = 4/A \text{ fb}^{-1}$
 - ▶ equiv. to $L = 3.8 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, $T = 4 \text{ weeks}$, duty cycle: 50%
- Detector: 100% efficient
 - ▶ Q^2 up to kin. limit $s \cdot x$
 - ▶ see talk by Elke
- Statistical errors only

Note: $L \sim 1/A$

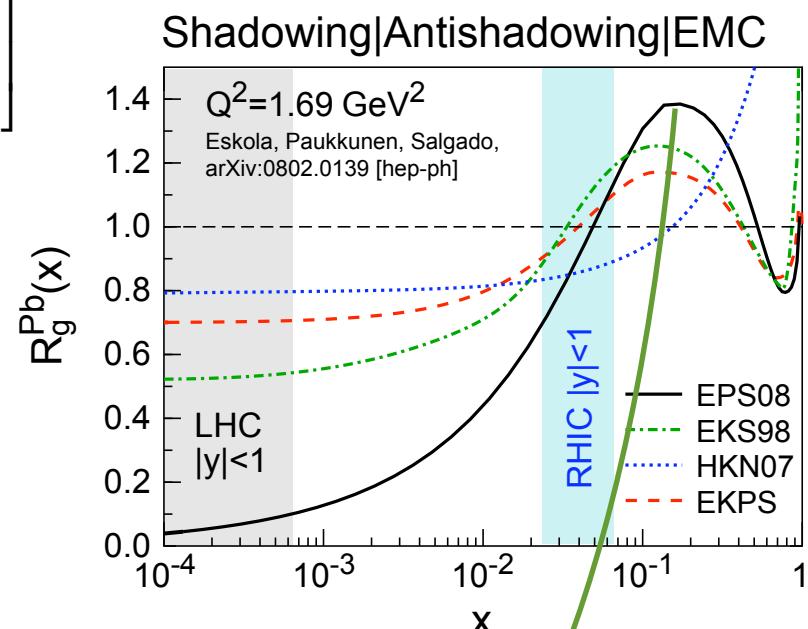
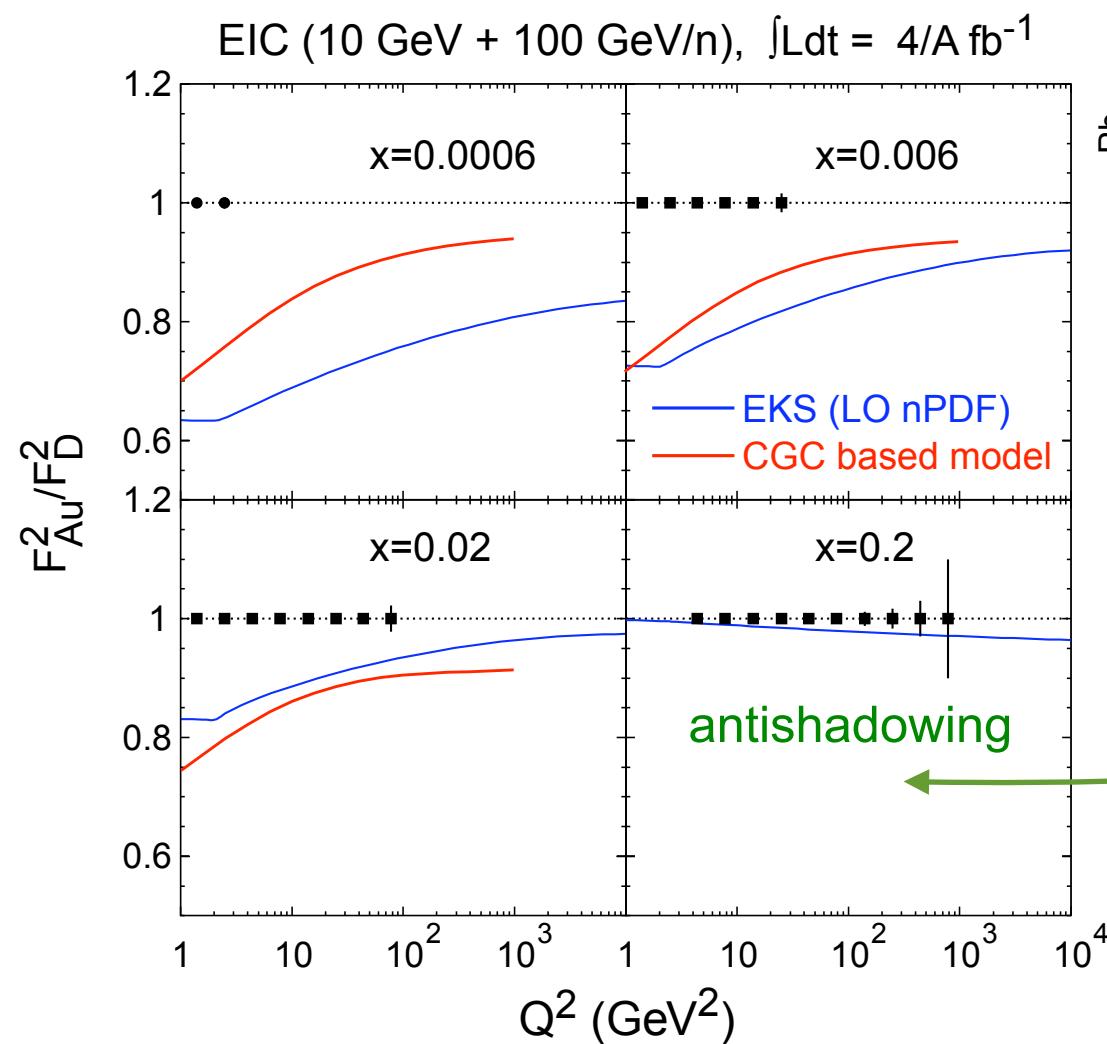
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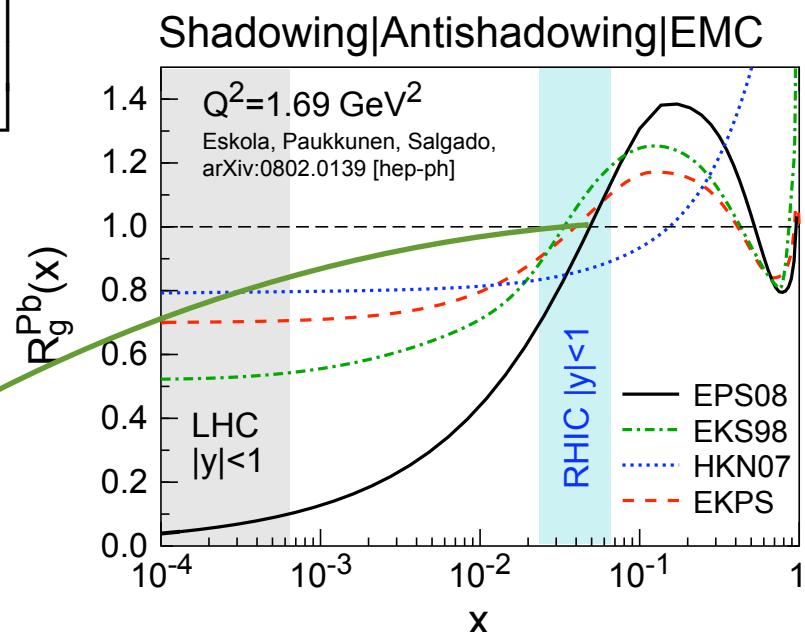
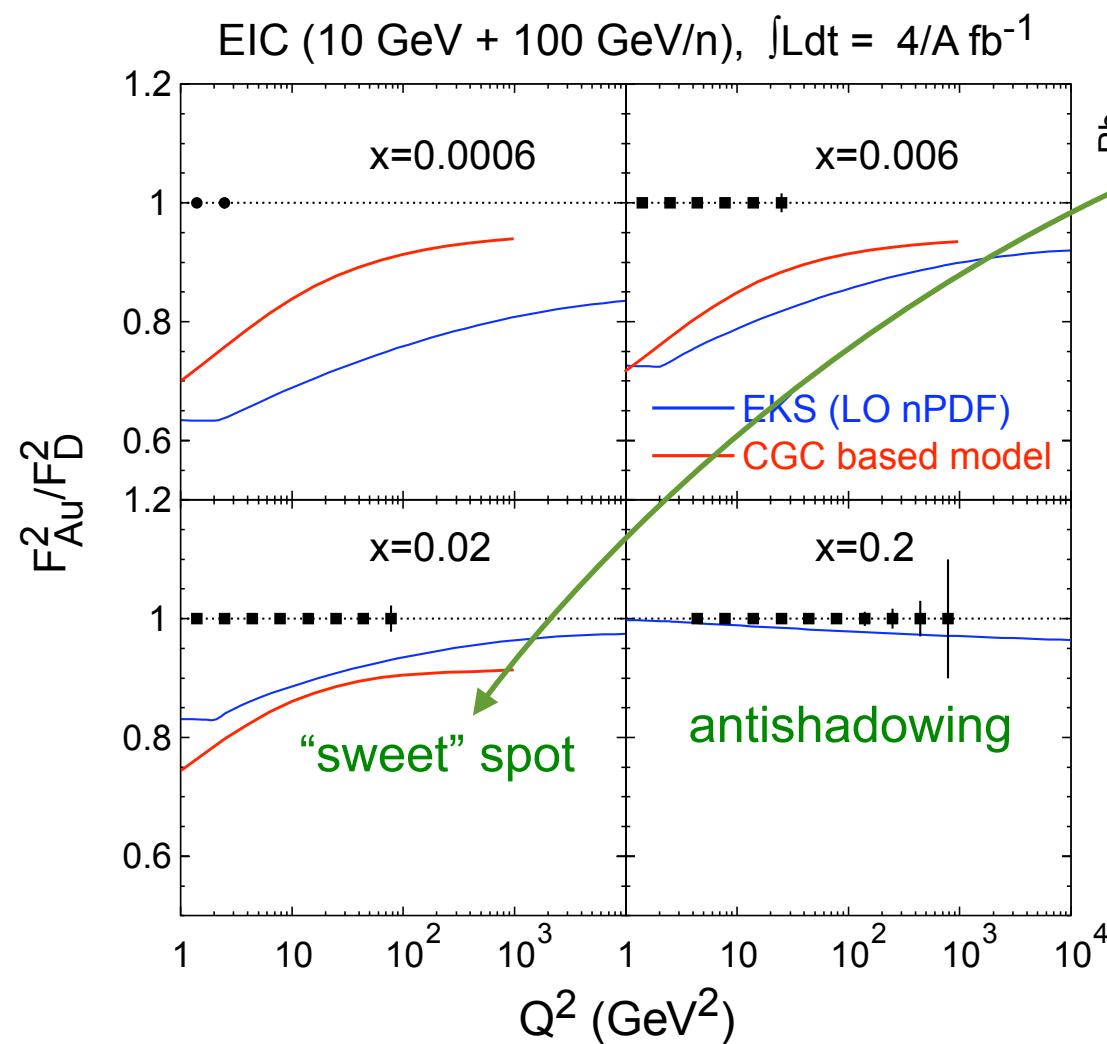
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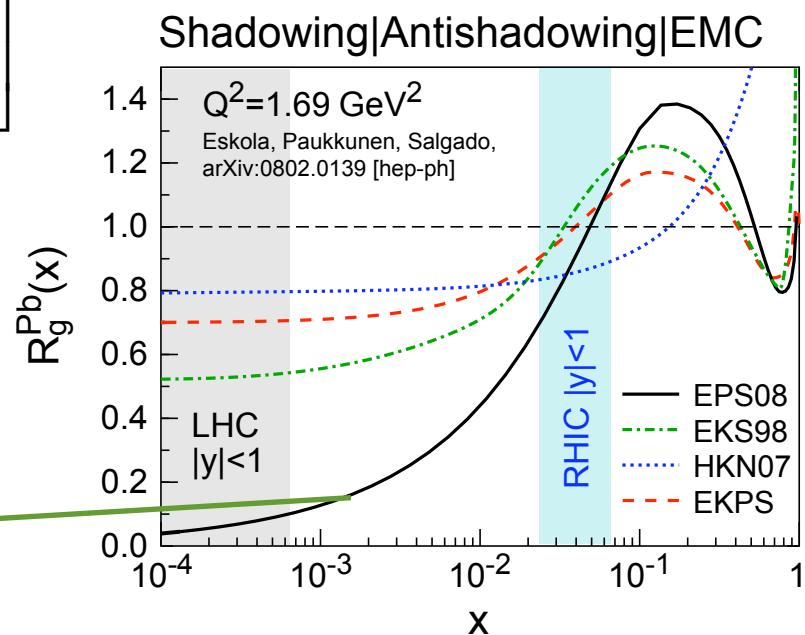
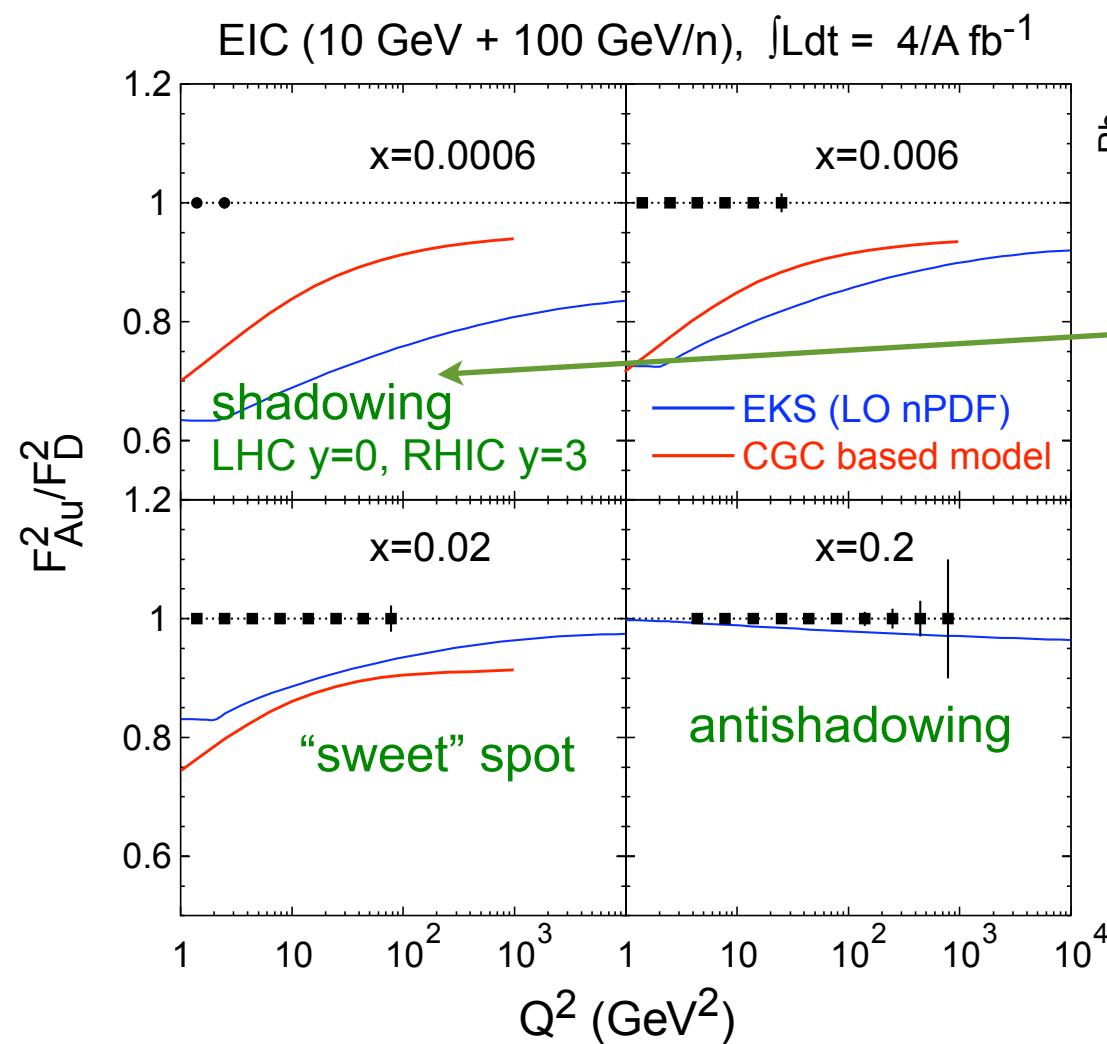
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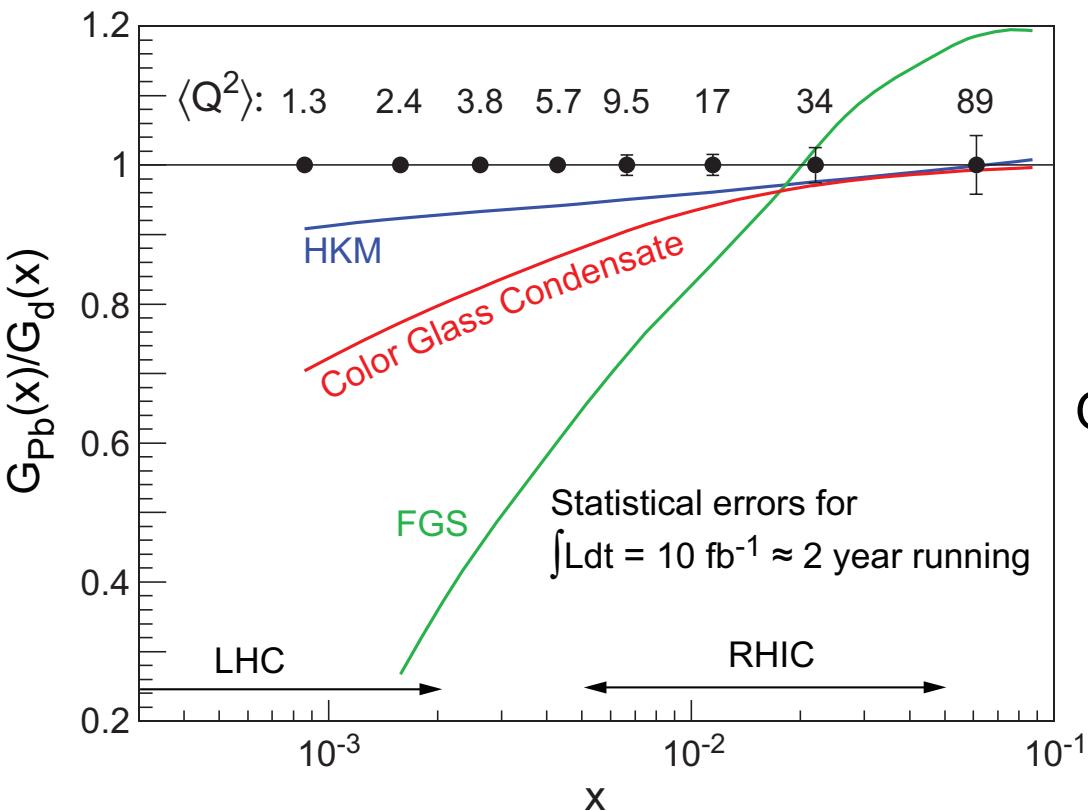
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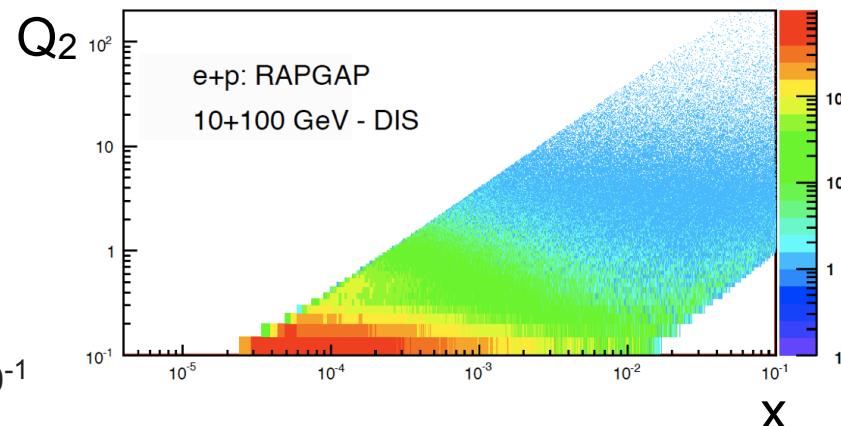


Measuring F_L with the EIC

F_L requires runs at various $\sqrt{s} \Rightarrow$ part of longer program



$F_L \sim \alpha_s G(x, Q^2)$
the most “direct” way
to $G(x, Q^2)$
 $\langle Q^2 \rangle$ reflect kinematic limits



Assumptions:

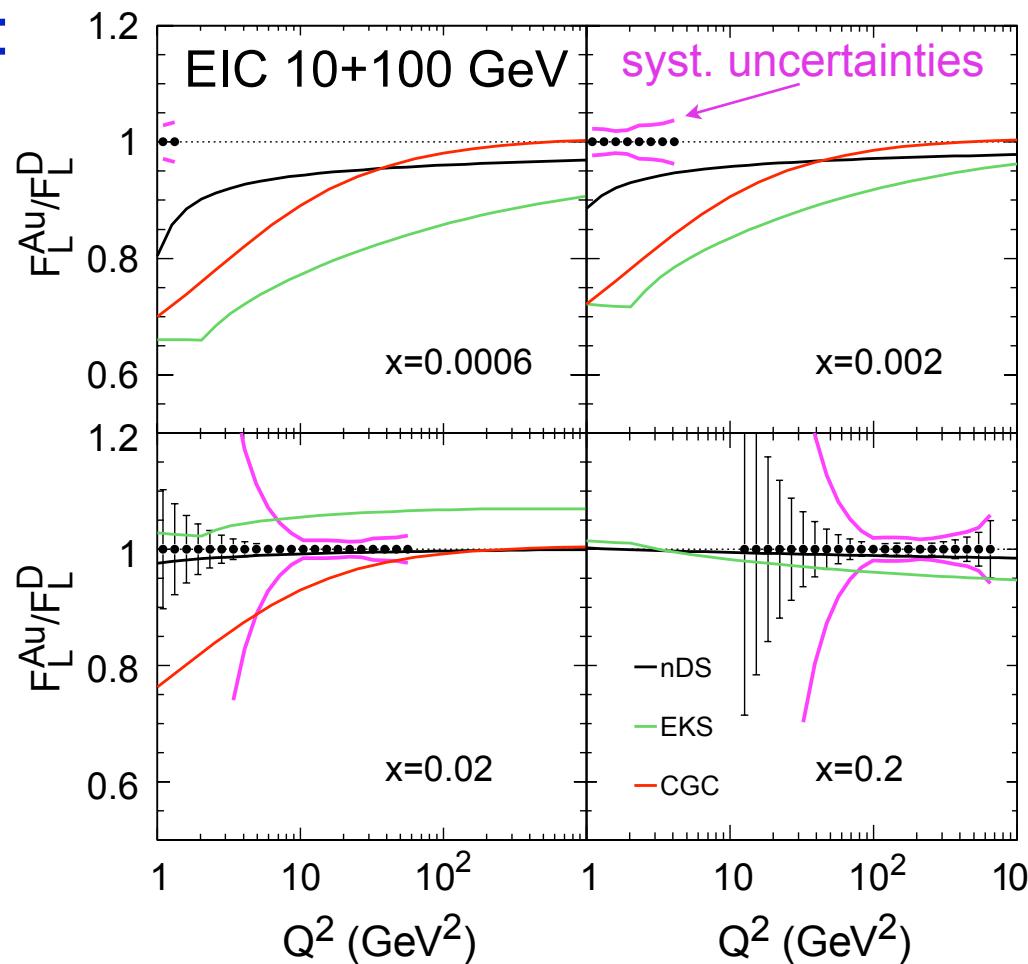
- $\int \mathcal{L} dt = 4/A \text{ fb}^{-1}$ (10+100) GeV
= $4/A \text{ fb}^{-1}$ (10+50) GeV
= $2/A \text{ fb}^{-1}$ (5+50) GeV
- Detector: 100% efficient
 - ▶ Q^2 up to kin. limit $s \cdot x$
- Statistical errors only

Measuring F_L : Systematic Uncertainties Rule

First attempt to get a feeling for systematic uncertainties
1% energy-to-energy normalization (can we do better?)

Conclusion from this study:

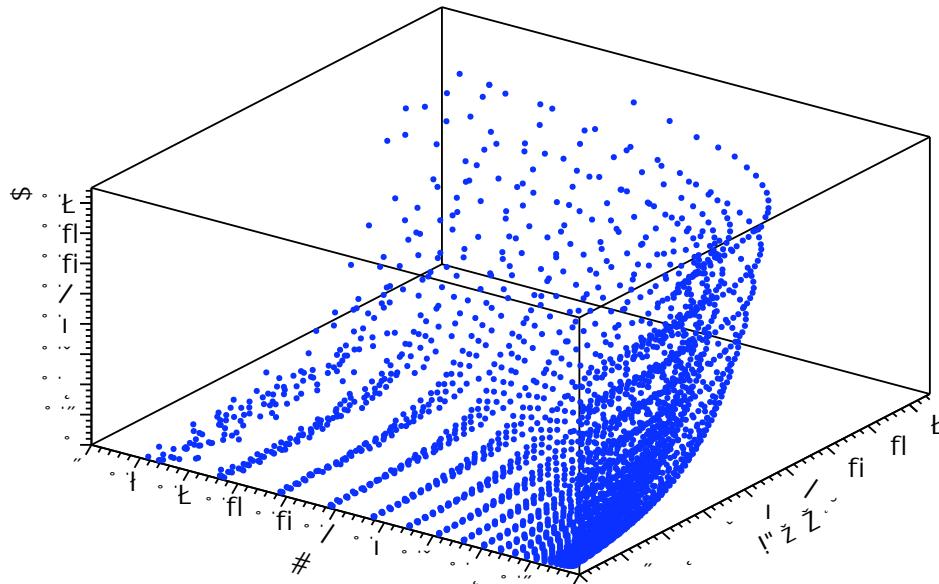
- Dominated by sys. uncertainties
- It makes little sense to collect more statistics when one is dominated by systematical errors
- Depending on x and Q^2 might be able take a hit in luminosity
⇒ need more detailed studies (detector simulations)



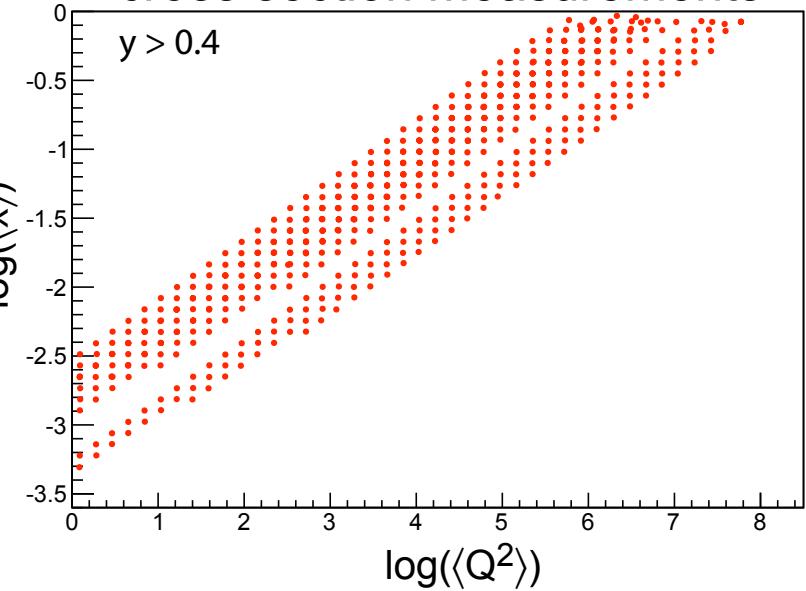
FL for Staged EIC: $E_e = 4$ GeV

F_L for electron energy fixed at 4 GeV and proton energies:
50, 70, 100, 250 GeV (4fb^{-1} each)

In order to extract F_L one needs at least two measurements of the inclusive cross section with “wide” span in inelasticity parameter y ($Q^2 = s_{xy}$)

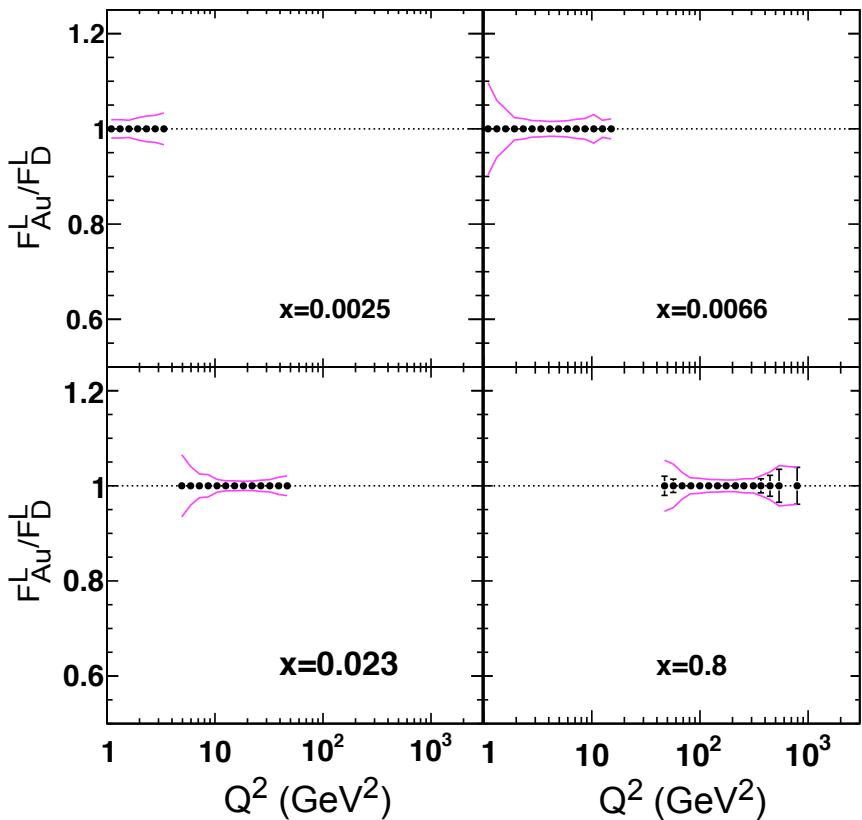


Coverage in x and Q^2 for inclusive cross section measurements

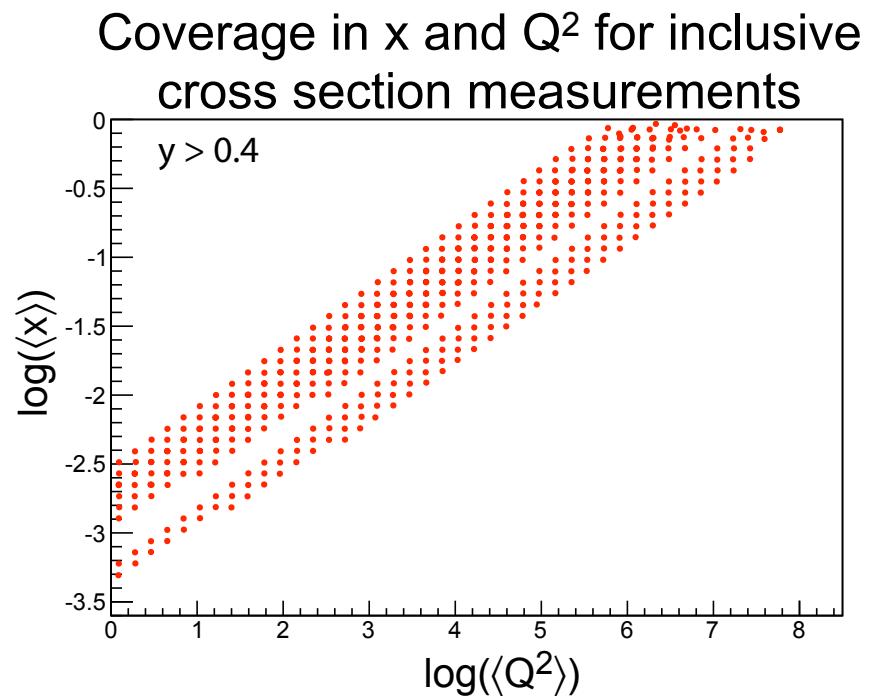


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The magenta lines shows the statistical and systematic error (1% uncertainty in normalization) added in quadrature.

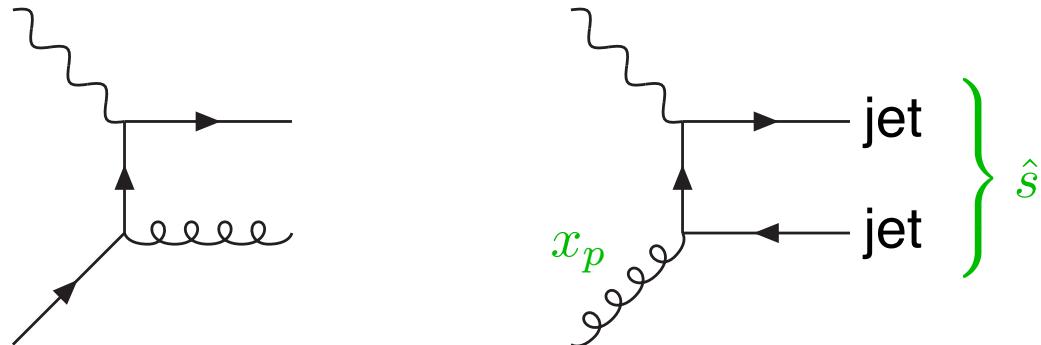


Again, the extraction of F_L is dominated by systematic uncertainties

Gluon Distribution from Jet Analysis at EIC

Jets: window to partons, DIS is a clean environment

“2+1 jets” becomes more interesting



Main formula:

$$\frac{d^2\sigma^{2+1}}{dx_p dQ^2} = \alpha_s [a g(x_p, Q^2) + b q(x_p, Q^2)]$$

Technique:

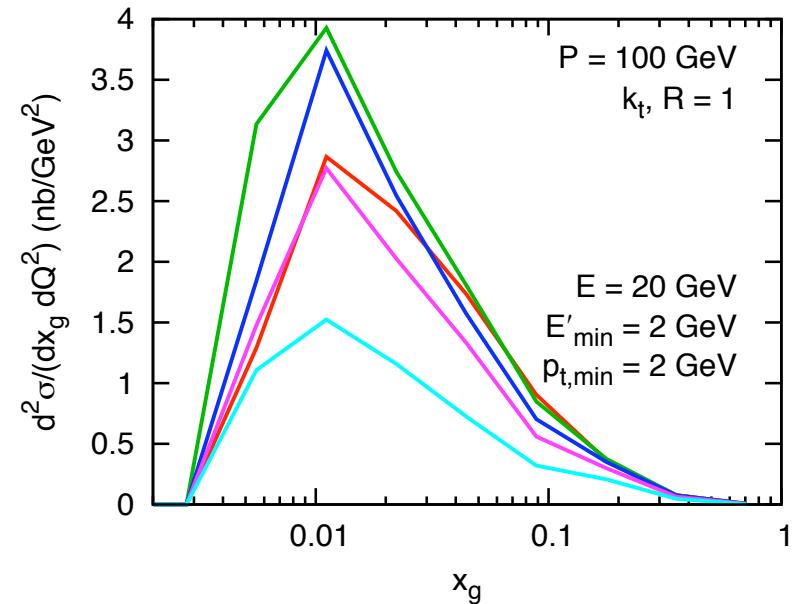
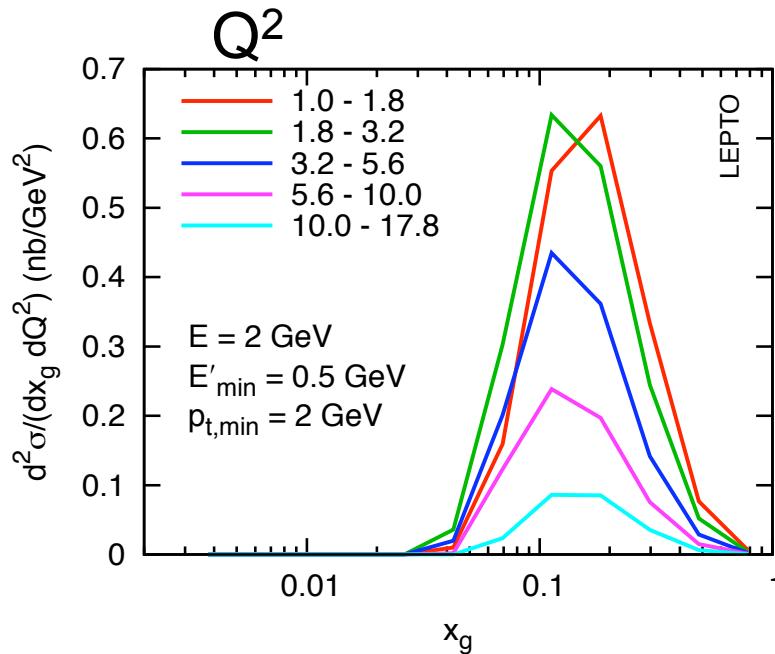
1. a and bq : matrix elements & quark piece from Monte Carlo
2. $x_p = x \left(1 + \frac{\hat{s}}{Q^2}\right)$
3. Extract the gluon distrib: $g_{\text{extr.}} = \frac{1}{a_{\text{MC}}} (\sigma_{\text{meas.}} - b_{\text{MC}} q)$

Results from Jets

Experimental cuts:

- Outgoing electron energy: E'_{\min}
- Minimal jet p_T : $p_{T,\min}$
- Azimuthal separation between the 2 jets: $\Delta\phi > \pi - \varepsilon$ (in the Breit frame — ensures that the 2 jets come from the hard scattering)
- Clustering: k_T algorithm with $R=1$ (large but OK in DIS)

Cross-section for gluon-initiated dijet events (obtained with LEPTO)

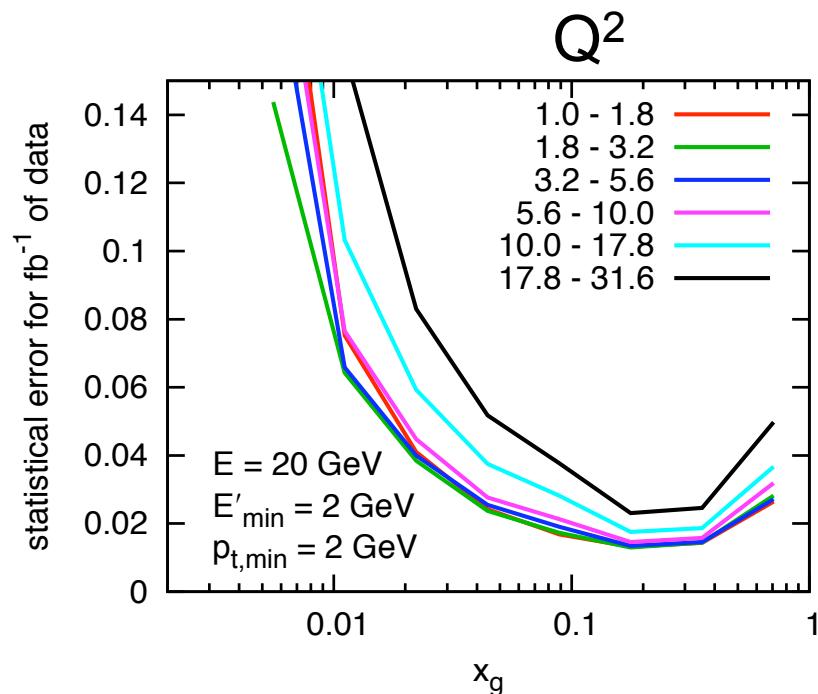
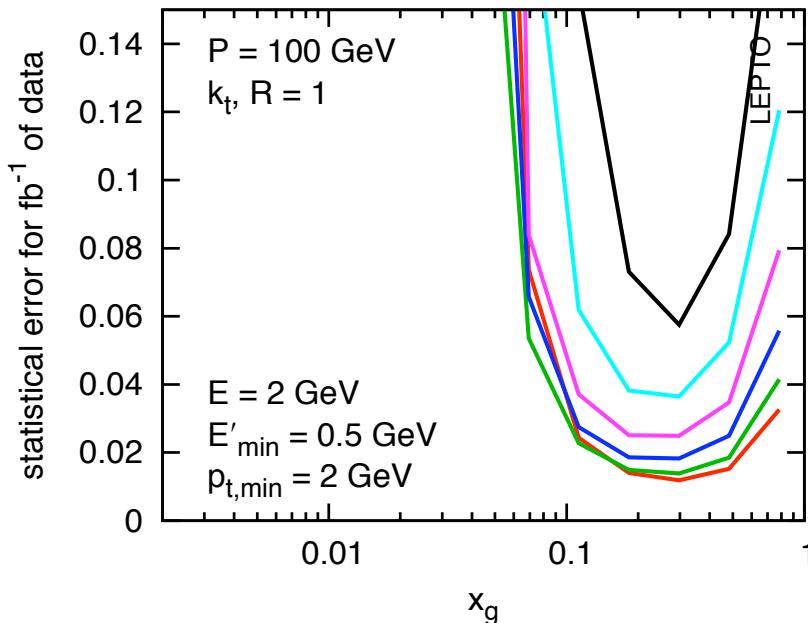


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Statistical errors assuming 1 fb^{-1}



Extracting $G(x, Q^2)$ from Diffractive Events

General Assumption:

Diffractive processes are the most sensitive means to probe $G(x, Q^2)$ and saturation since $\sigma \propto G(x, Q^2)^2$

Caveats:

- Theoretical
 - ▶ How to extract G from σ ?
 - ▶ At what scale (Q^2) and what x are we probing G ?
- Experimental
 - ▶ Detecting diffractive eA events ?
 - testing breakup of nuclei versus rapidity gap
 - ▶ Separating coherent from incoherent processes
 - How to detect breakup of nuclei ?
 - ▶ How to measure t ?

Extracting $G(x, Q^2)$ from Diffractive Events

Smoking Gun (?): exclusive diffractive vector meson production

pQCD:
$$\frac{d\sigma_L^{\gamma^* A \rightarrow V A}}{dt} \Big|_{t=0} \propto \frac{\alpha_S^2(Q^2)}{Q^6} \boxed{[xG_A(x, Q^2)]^2}$$

Brodsky et al.
Frankfurt,Koepf,Strikman

but: only valid at large Q^2 (\Rightarrow large x since $Q^2 \sim x \cdot s$)

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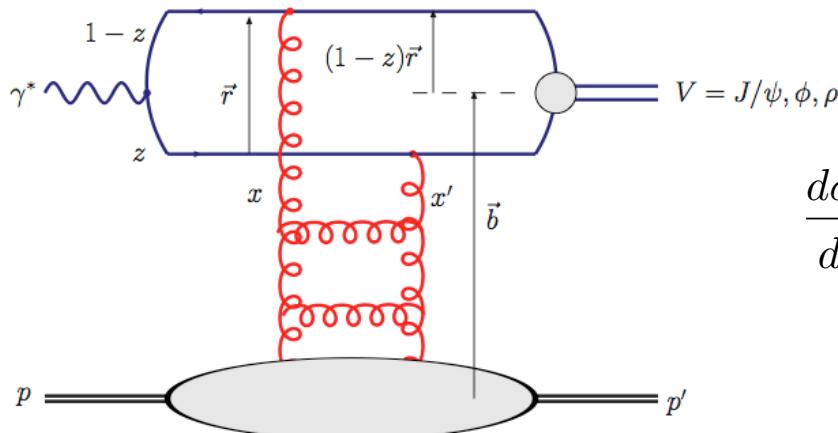
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Dipole model:

Kowalski,Motyka,Watt

$$\frac{d\sigma_{T,L}^{\gamma^* p \rightarrow p V}}{dt} = \frac{1}{16\pi} \left| \int dr (2\pi r) \int_0^1 \frac{dz}{4\pi} \int db (2\pi b) (\Psi_V^* \Psi)_{T,L} J_0(b\Delta) J_0([1-z]r\Delta) \frac{d\sigma_{q\bar{q}}}{d^2\vec{b}} \right|^2$$



$$\frac{d\sigma_{q\bar{q}}}{d^2\vec{b}} = 2 \left[1 - \exp \left(-\frac{\pi^2}{2N_c} r^2 \alpha_S(\mu^2) x g(x, \mu^2) T(b) \right) \right]$$

Glauber-Mueller

Modeling Diffractive VM Production

Implemented various dipole models (b-Sat, b-CGC) in a single program (xdvmp) for ep and recently for eA. Various VM wave functions are implemented. The implementation of the pQCD model is underway.

The dipole model describes VM (J/ψ , ϕ , ρ) production at HERA very well.

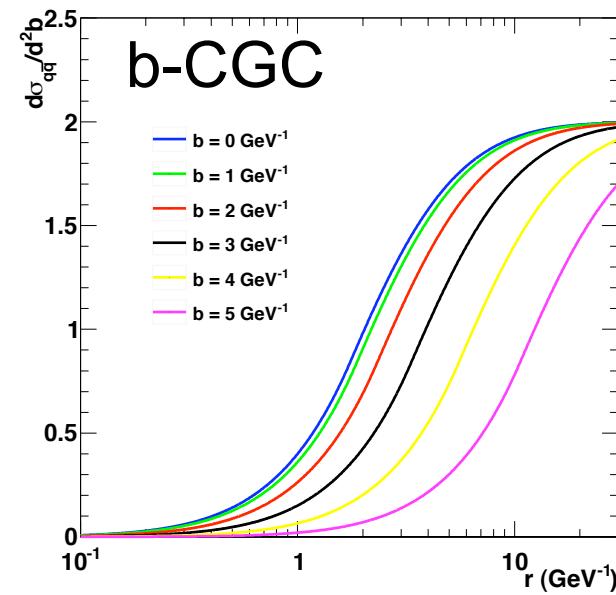
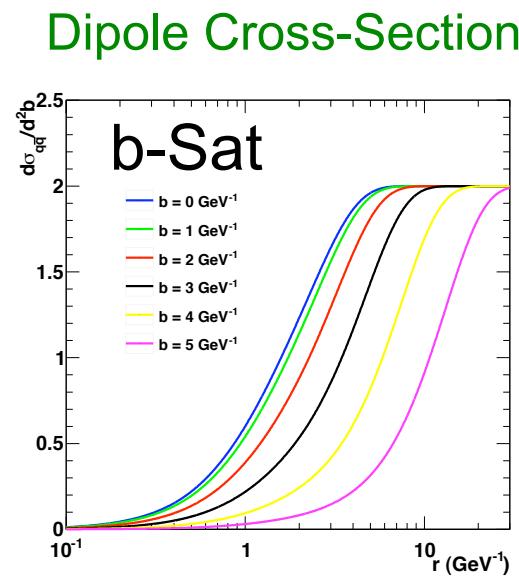
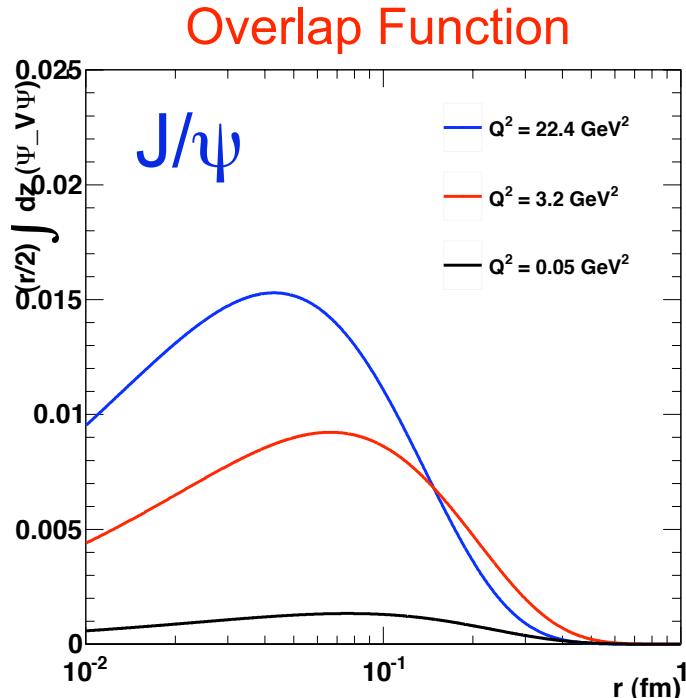
Both will be used to test sensitivity to different $G(x, Q^2)$ and can be used in detector simulations.

First Lessons Learned for EIC

Cross-section for production of final state VM:

$$\frac{d\sigma_{T,L}^{\gamma^* p \rightarrow Ep}}{dt} = \frac{1}{16\pi} |\mathcal{A}_{T,L}^{\gamma^* p \rightarrow Ep}|^2 = \frac{1}{16\pi} \left| \int d^2 r \int_0^1 \frac{dz}{4\pi} \int d^2 b (\Psi_E^* \Psi)_{T,L} e^{-i[\mathbf{b} - (1-z)\mathbf{r}] \cdot \Delta} \frac{d\sigma_{q\bar{q}}}{d^2 b} \right|^2$$

Amplitude Overlap between photon and VM wave function Dipole Cross-Section

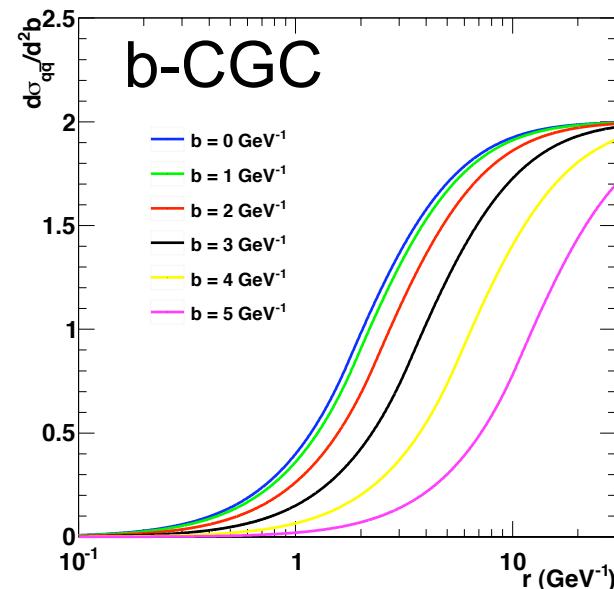
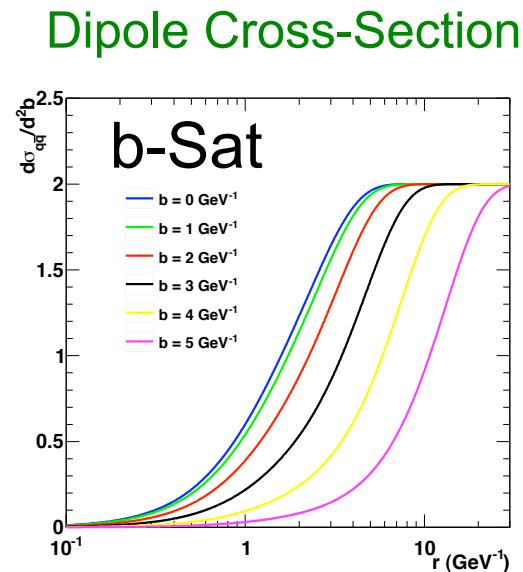
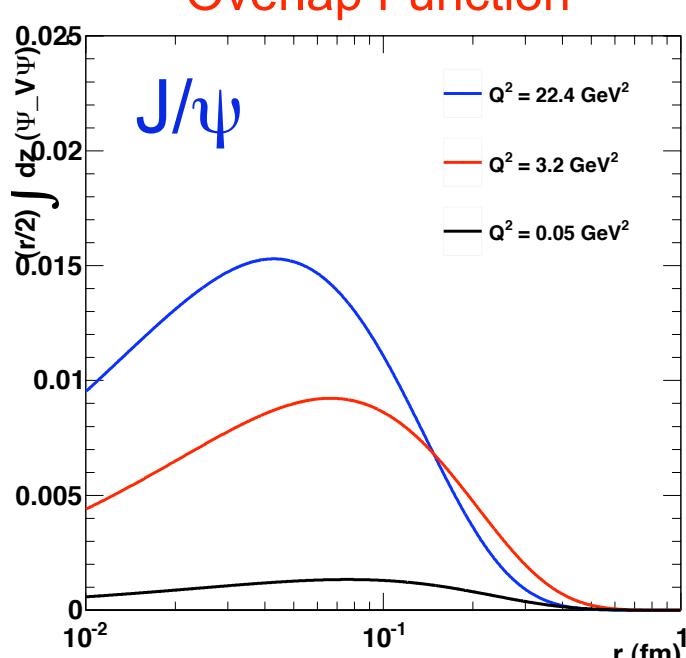


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First Lessons Learned for EIC

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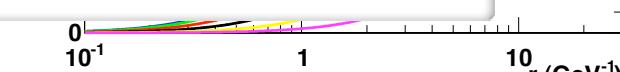
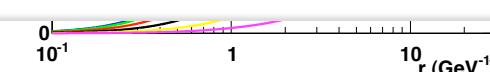
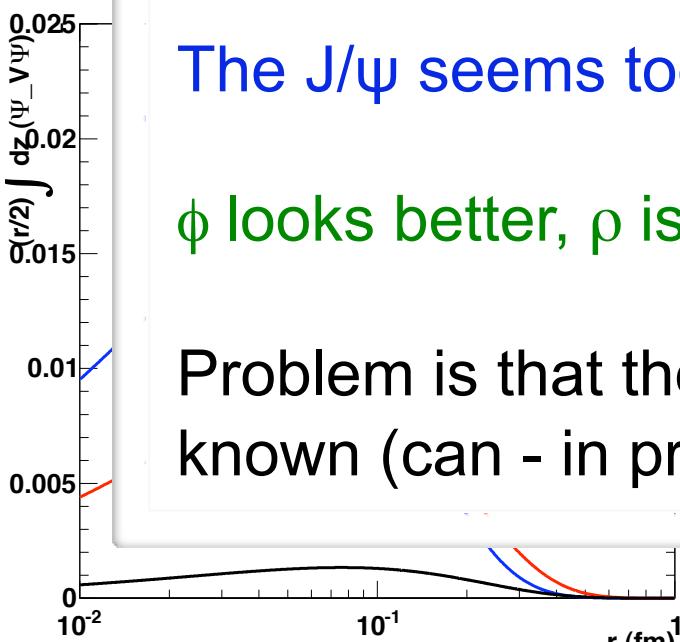
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Overlap function vanishes for large dipole radii where saturation kicks in ($Q \sim 1/r$)

The J/ψ seems too small to probe saturation physics

ϕ looks better, ρ is ideal

Problem is that the wave functions for ρ , ϕ are less known (can - in principle - be solved)

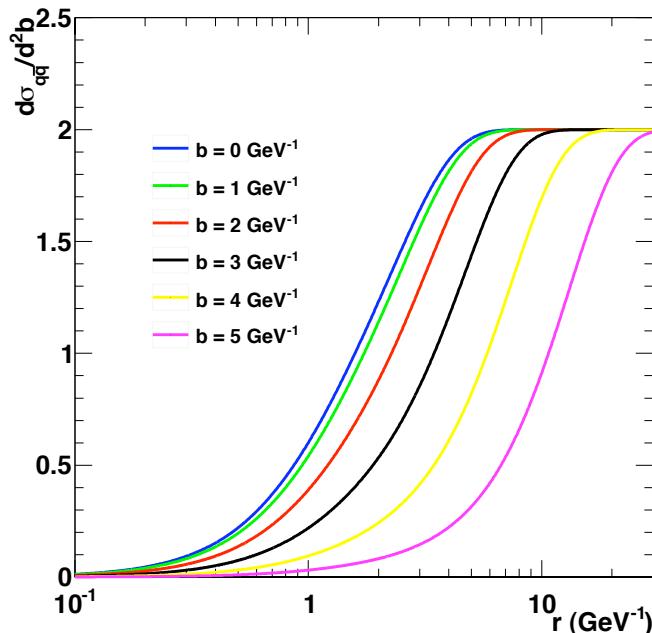


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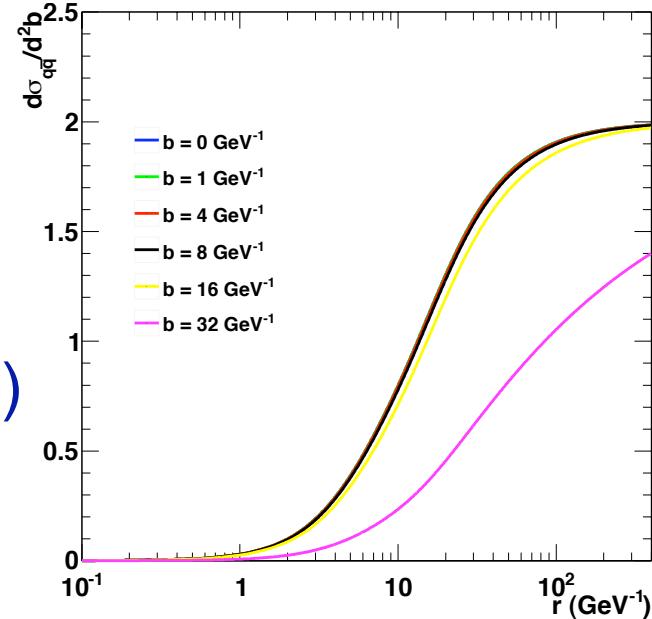
From ep to eA ...

(All xdvmp)

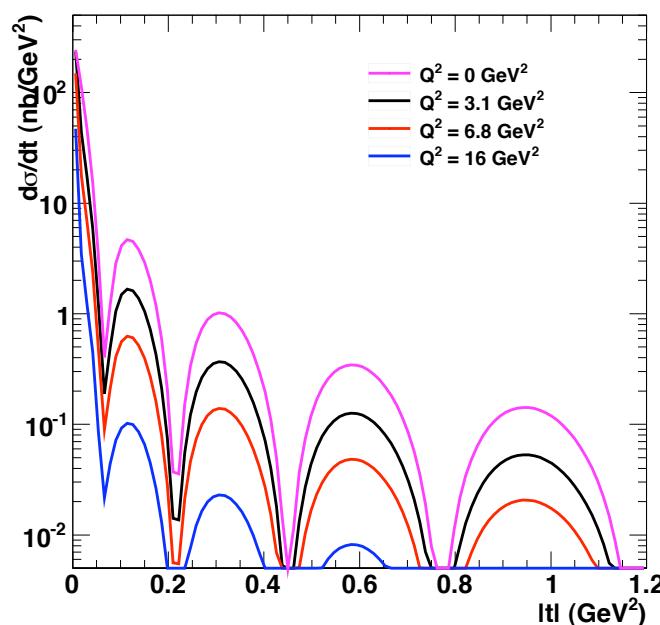
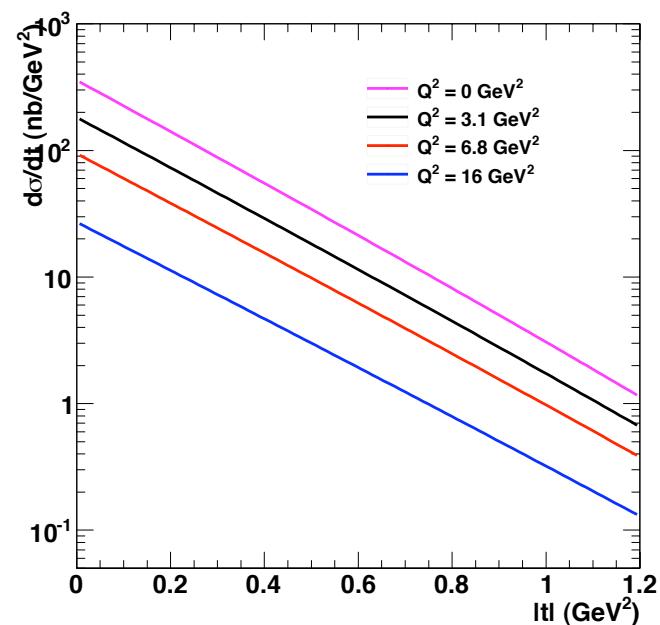
ep →



eA →

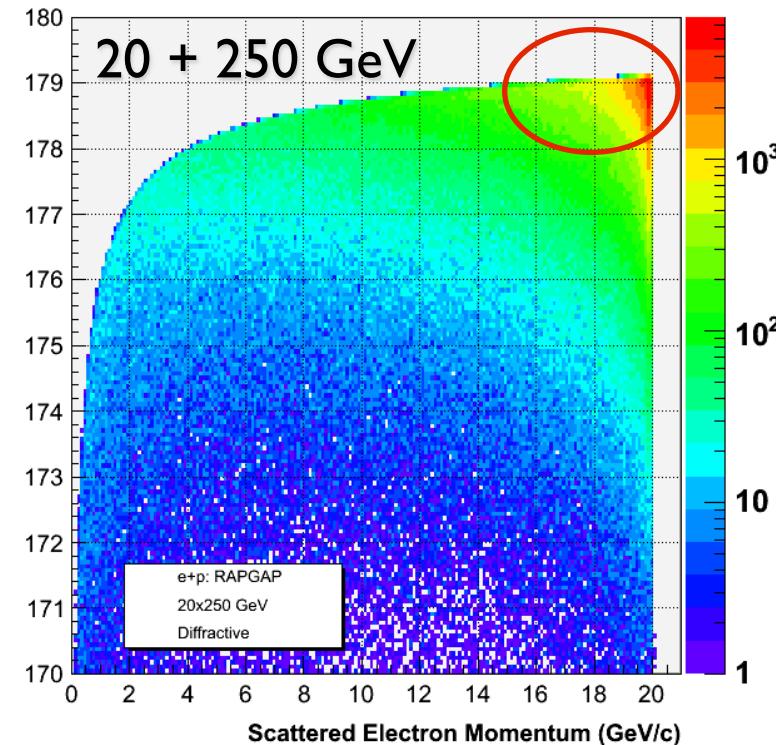
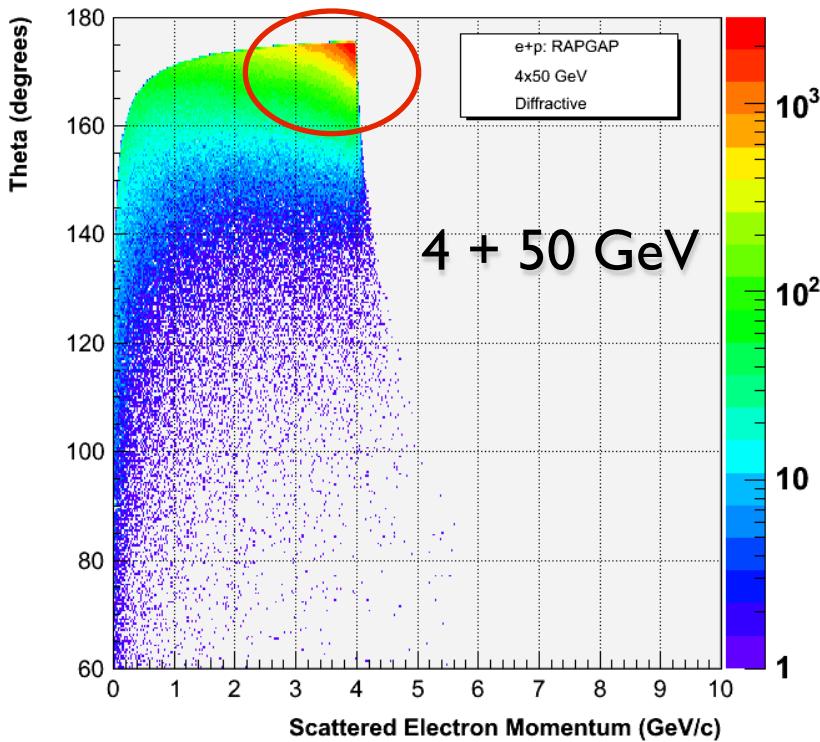


Note: eA is less
b dependent than
ep (which is good)



Diffractive Physics is Experimentally Hard

Scattered Electron $\theta(p)$



Stringent constraints on detector:

Need to measure electrons (PID + p) down to very low angles (up to 1° off the beam line)
⇒ need dipole magnet(s) to bend e in “sane” region

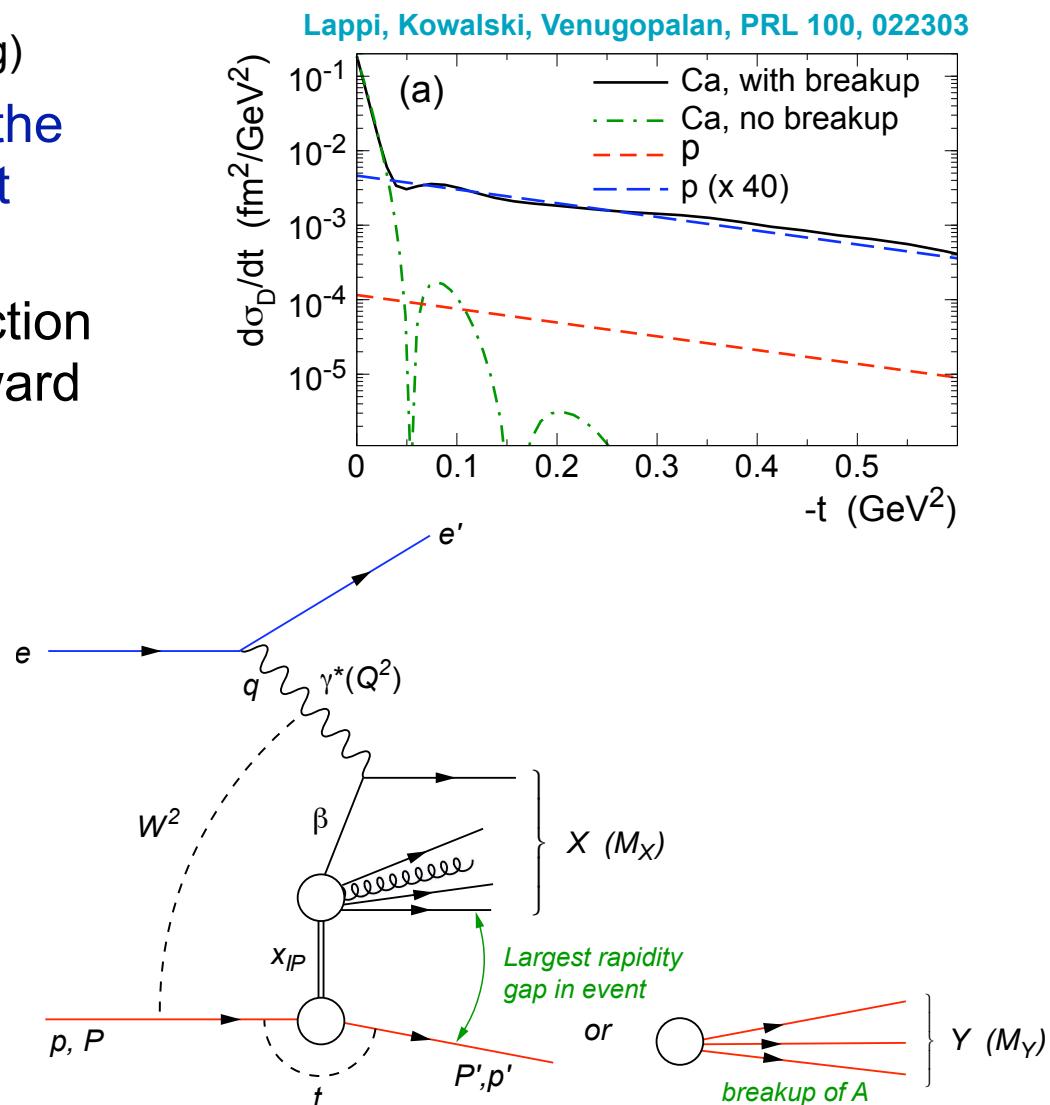
Identifying Diffractive Events

Reminder (see previous IAC meeting)

- Beam angular divergence limits the smallest outgoing $p(A)$ angle that can be measured
- Cannot measure coherent diffraction in heavy ions (small t) using forward spectrometry (Roman Pots)
 - ▶ separate ion only if $p_T > p_{T,\min}$
 - ▶ possible for p and light ions

$$\theta = \sqrt{\frac{\epsilon}{6\pi\beta^*}}$$

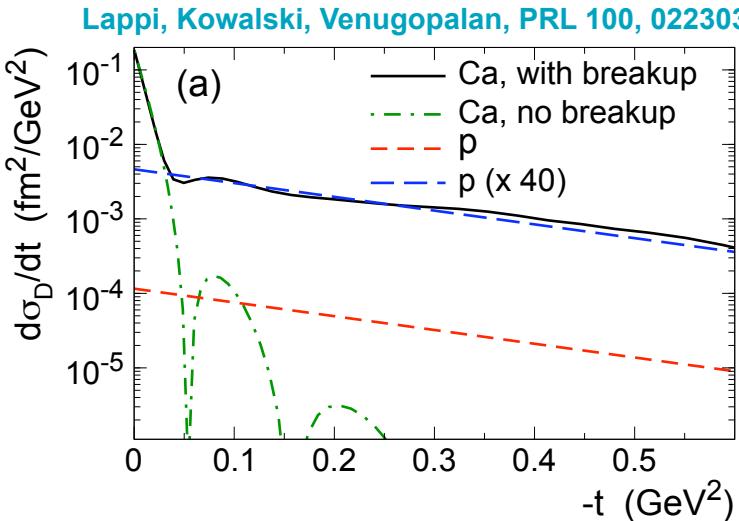
species (A)	p_T^{\min} (GeV/c)
d (2)	0.02
Si (28)	0.22
Cu (64)	0.51
In (115)	0.92
Au (197)	1.58
U (238)	1.90



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- Need to rely on rapidity gap method
 - ▶ simulations look good
 - ▶ high efficiency, high purity possible
 - ~1% contamination,
 - ~80% efficiency
 - ▶ depends critically on hermeticity of detector
- Very critical:
 - ▶ identifying incoherent diffraction
 - ▶ Zero-Degree Calorimeter & Forward Spectrometer
 - ▶ New idea: Use U instead of Au (fission)

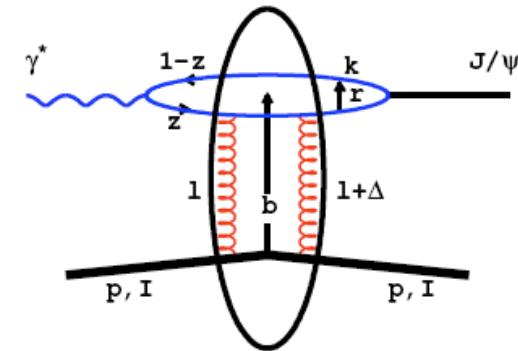
New: Probing Gluonic Structure of Nuclei

Basic Idea: Studying diffractive exclusive J/ψ production at $Q^2=0$ (photo-production)

(H. Kowalski & A. Caldwell)

Ideal probe

- large photo-production cross sections
- t can be derived from e , e' , and J/ψ alone
 - ▶ no measurement of ion momentum necessary
 - ▶ beam electron $p_T < 1$ MeV (0.2 with cooling MeV) for $E < 5$ GeV
 - ▶ scattered electron can be detected in the forward detector (beam optic needs to be studied)
- small width well separated from background
- J/ψ dipole interacts only by 2g exchange at low x
 - ▶ process is well understood in QCD



Probing Gluonic Structure of Nuclear Forces

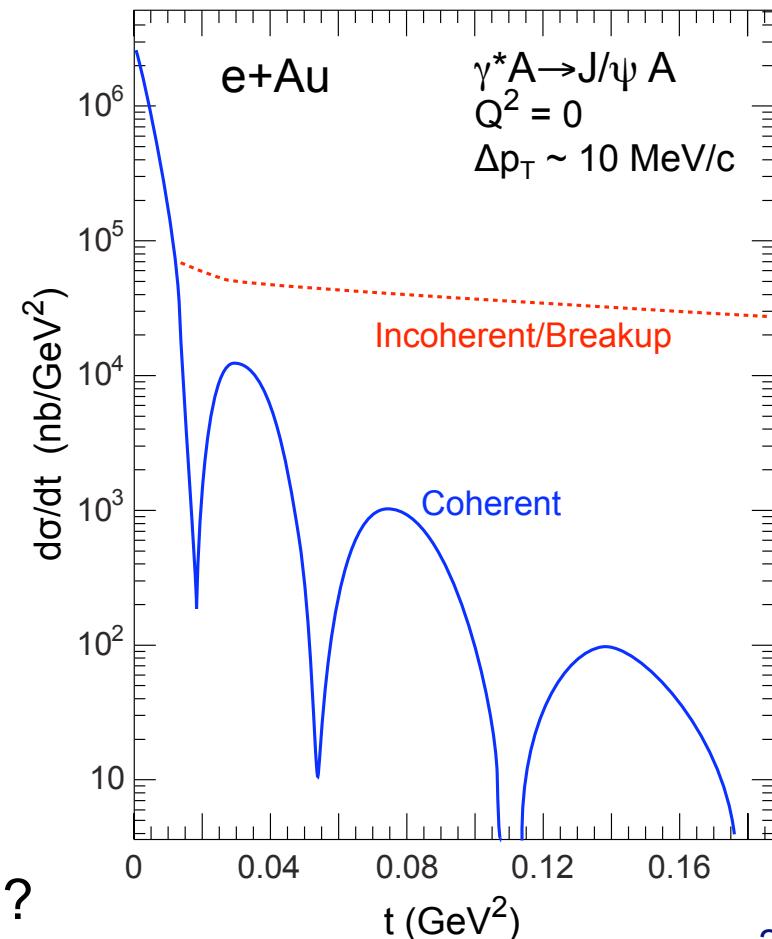
Simplified assumption for proof of principle:

- Random and uncorrelated distribution of nucleons within the nucleus
- Shape of the nucleus given by the Woods-Saxon distribution
- Average (sum) over all configurations
- Fourier transform the average $\Rightarrow d\sigma_A/dt$

Promising method to measure
gluon form factor F_g in nuclei

Crucial: detecting breakup of nuclei

- incoherent - nucleus gets excited or breaks up, no additional particles are produced
- Need suppress background by factor 100
- Dynamics of nuclear disintegration?
 - ▶ studies underway (QMD?), Uranium?



Probing Gluonic Structure of Nuclear Forces

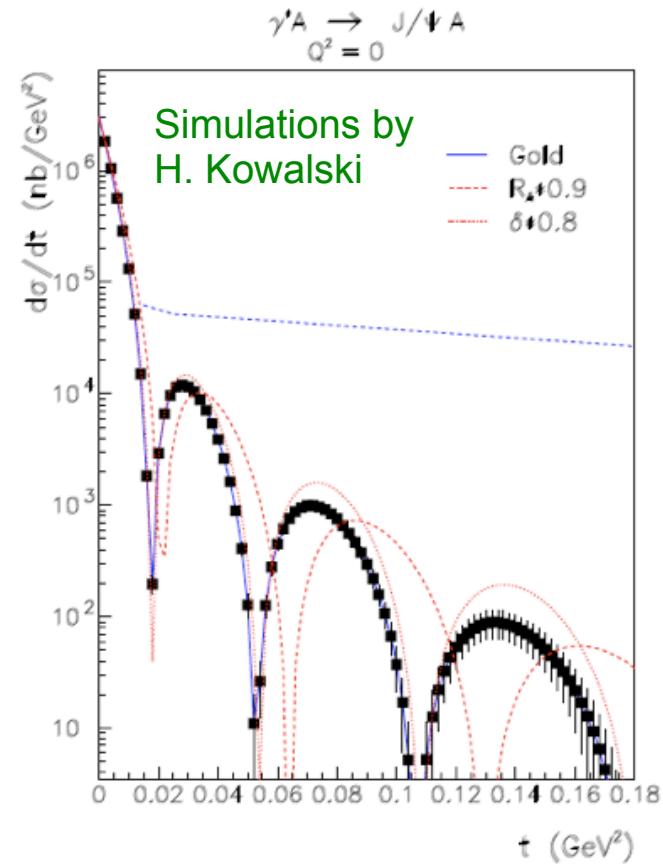
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Summary

Study of measurements of $G(x, Q^2)$ in progress

- F_2 (existing studies but not updated yet)
- F_L (EIC & staged EIC) - (R. Debbe)
- 2+1 jets (EIC & staged EIC) - (G. Soyez)
- Diffractive VM production (M. Lamont, TU, R. Venugopalan, M. Savastio) - no error evaluation yet but all we need is there

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New promising idea to measure gluonic structure of nuclear forces (**Gluonic formfactor of nuclei**)

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Next Steps

- Further investigate nuclear breakup (H. Kowalski)
- Simulation on diffractive VM (M. Lamont, TU)
- Run measurements through detector simulation (see Elke's talk)